

Title: "Motor Control and Regulation for a Flywheel Energy Storage System"

Abstract: This talk will focus on the motor control algorithms used to regulate the flywheel system at the NASA Glenn Research Center. First a discussion of the inner loop torque control technique will be given. It is based on the principle of field orientation and is implemented without a position or speed sensor (sensorless control). Then the outer loop charge and discharge algorithm will be presented. This algorithm controls the acceleration of the flywheel during charging and the deceleration while discharging. The algorithm also allows the flywheel system to regulate the DC bus voltage during the discharge cycle.

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Motor Control and Regulation for a Flywheel Energy Storage System.

Dr. Barbara H. Kenny

11 April 2003

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Outline of Presentation

- NASA GRC flywheel system
- Control of permanent magnet motor
- Position information feedback techniques
- Flywheel charge & discharge control
- Experimental results
- Conclusions & future work

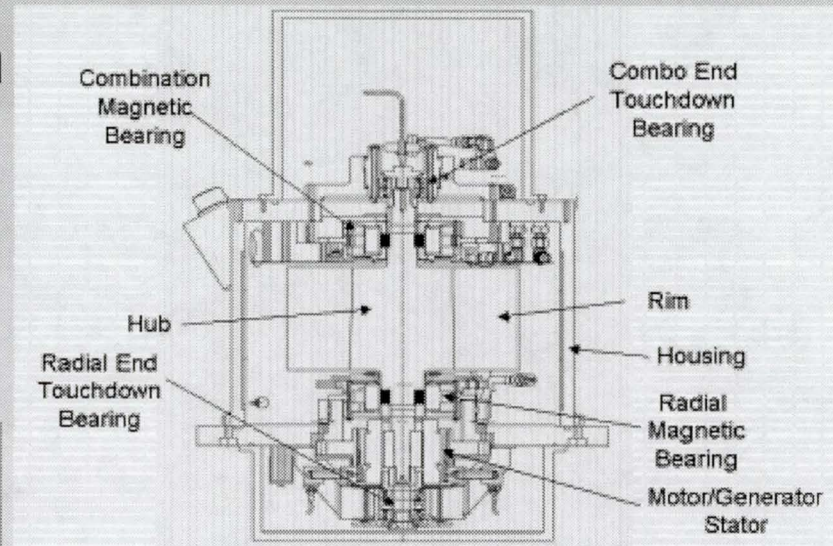
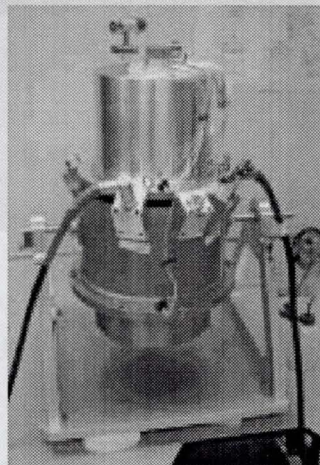
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NASA GRC Flywheel System

- Composite flywheel rim
- Magnetic bearings
- Touchdown bearings
- Motor/generator



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Flywheel System Control Room



•Motor Control

•Magnetic Bearing Control



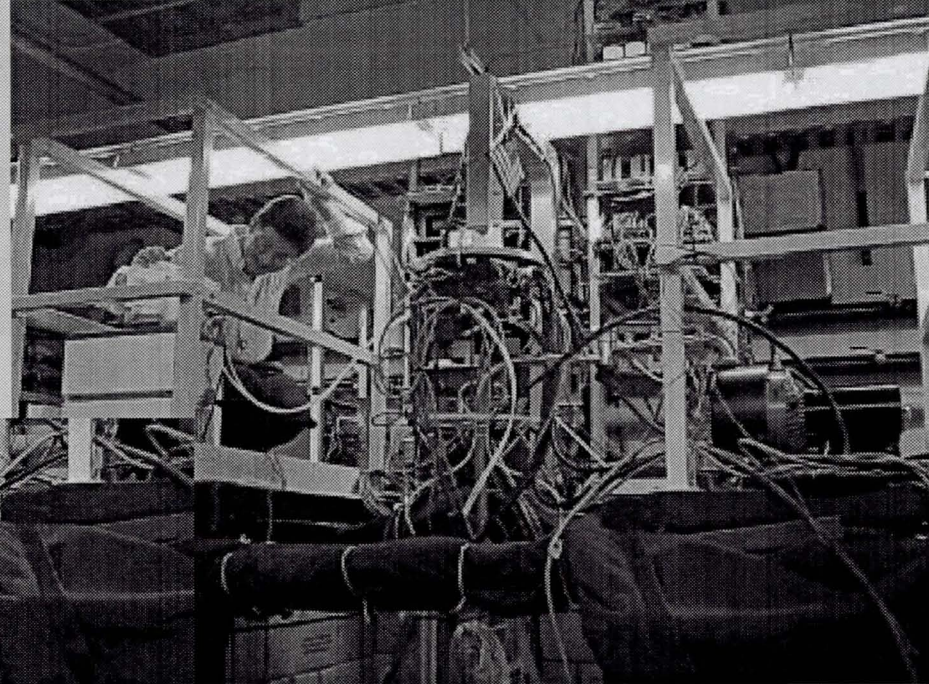
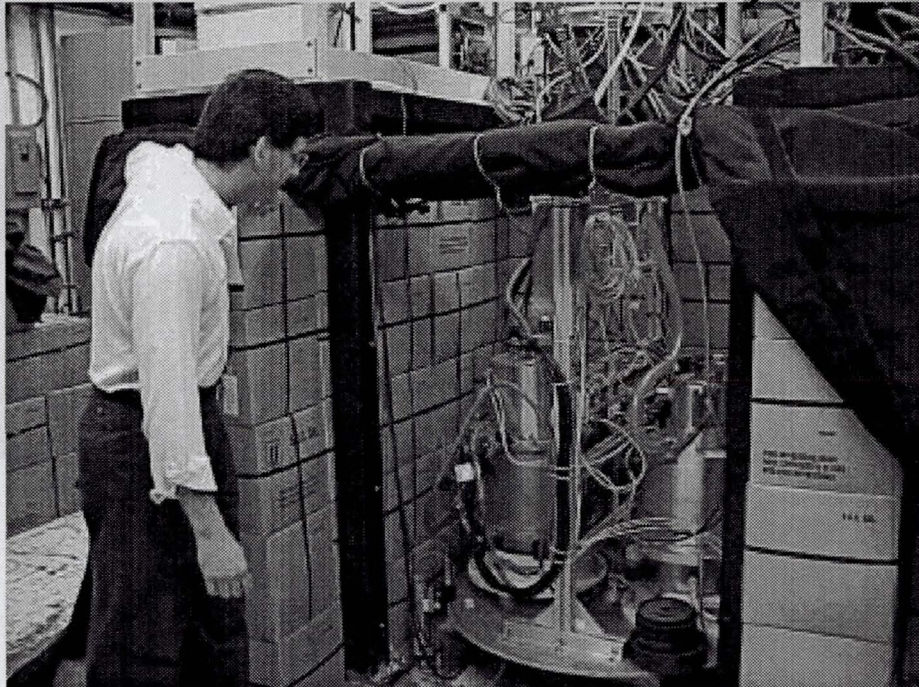
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Electronics

Flywheel modules



Flywheel test
facility

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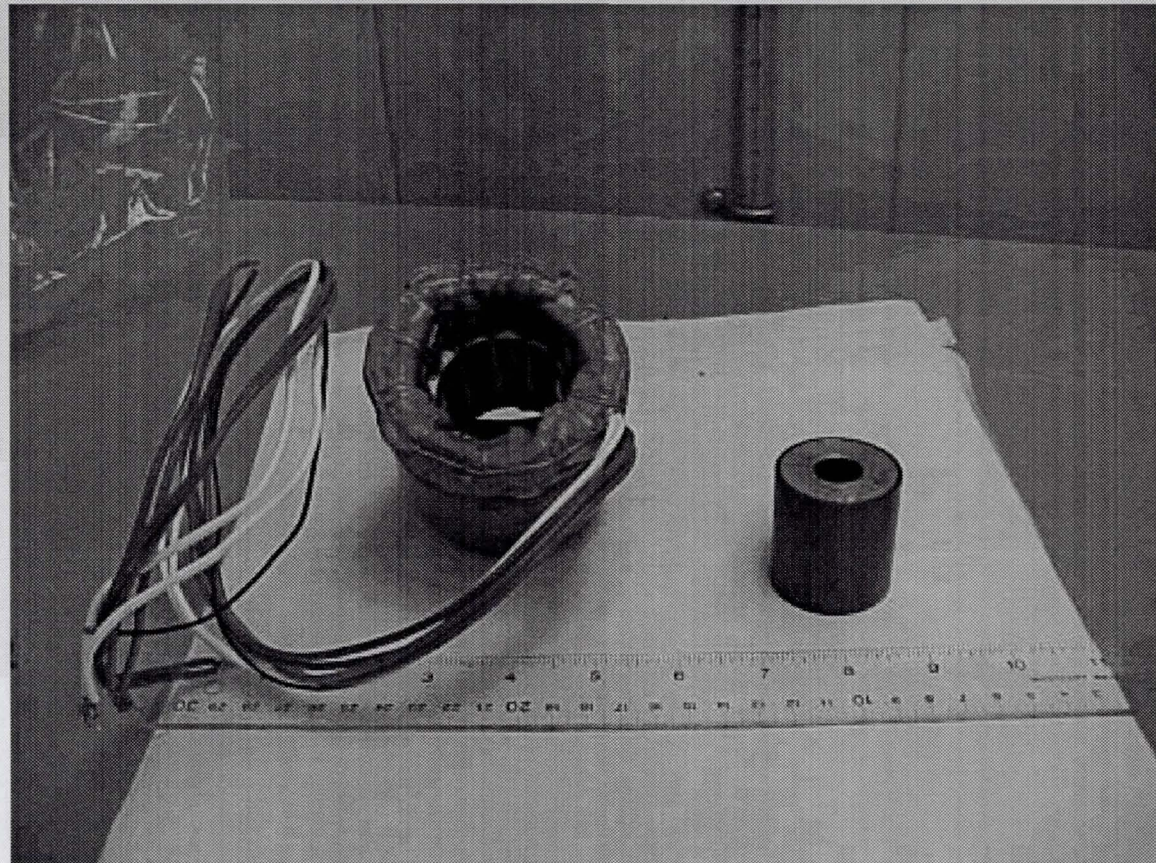
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Flywheel System Motor

- Permanent magnet synchronous machine

2 poles,
3 phase,
65 volts peak,
60,000 rpm



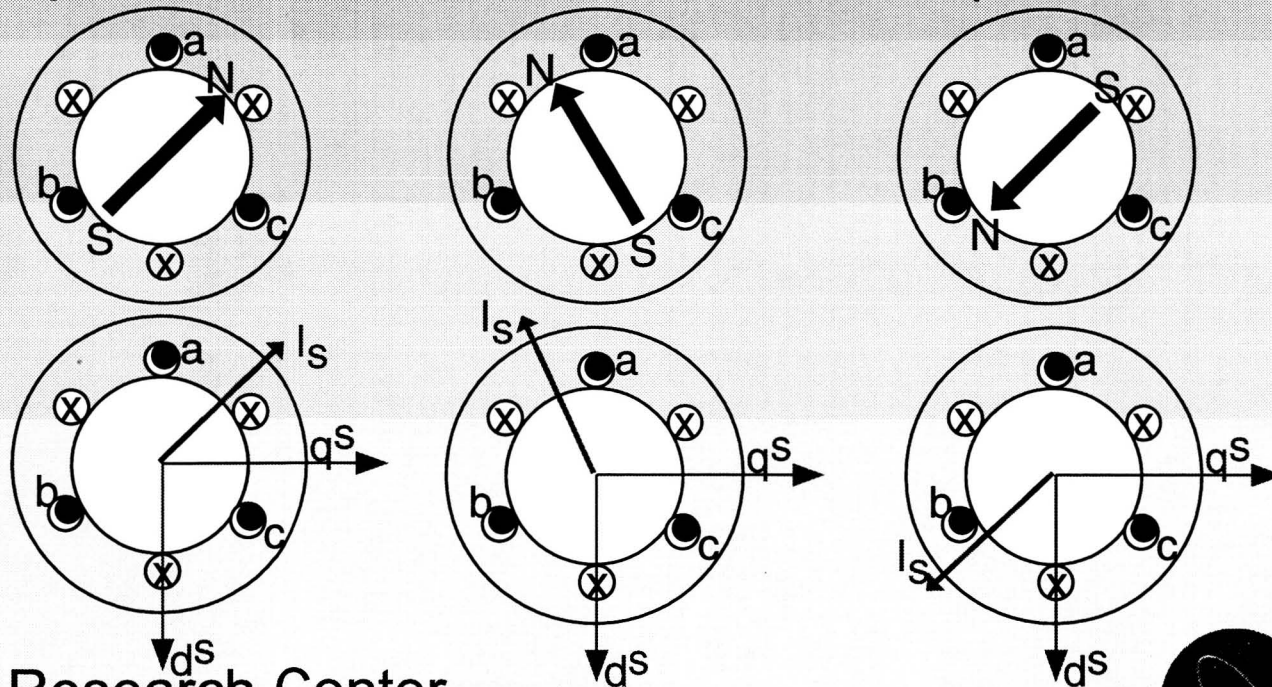
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PM Machine Principles of Operation

- Stator
 - 3 phase winding $\Rightarrow$ rotating magnetic field
 - Effect of 3 phase currents mathematically represented as a current vector on d-q axes



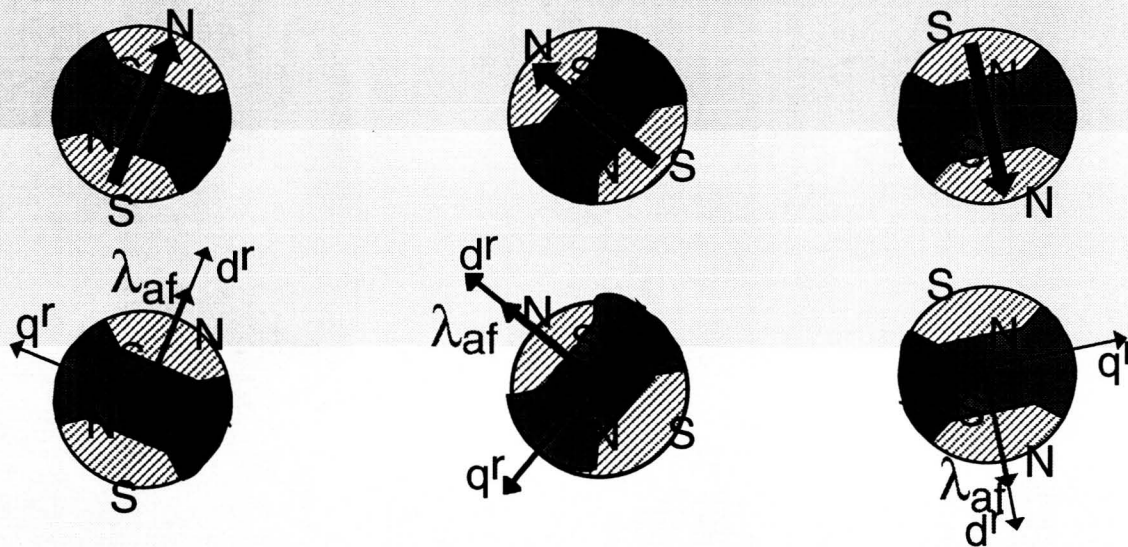
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PM Machine Principles of Operation (II)

- Rotor
 - Permanent magnets provides magnetic field



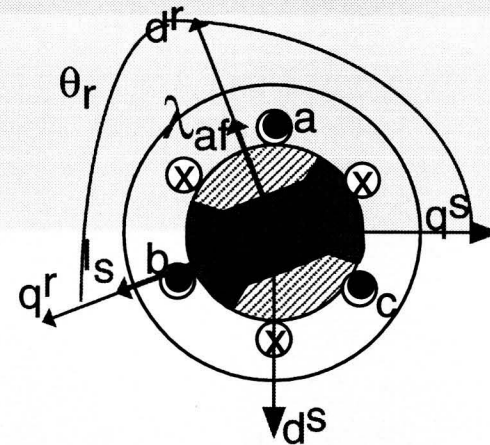
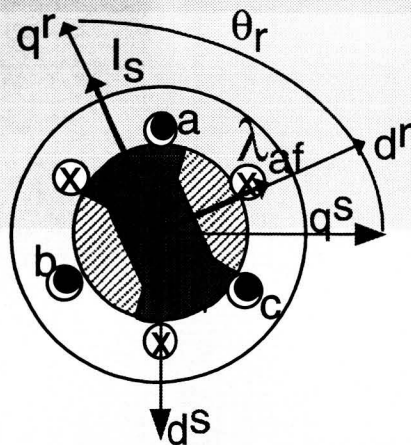
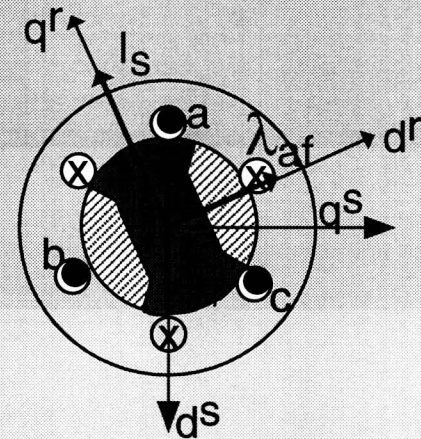
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PM Machine Principles of Operation (III)

- If stator current vector and rotor magnetic field are perpendicular $\Rightarrow T = \frac{3}{2} \frac{P}{2} |I_s| \lambda_{af}$
- Current must be properly controlled to maintain 90 degree angle with rotor field.
- Need to know location of rotor field vector, λ_{af} , and θ_r



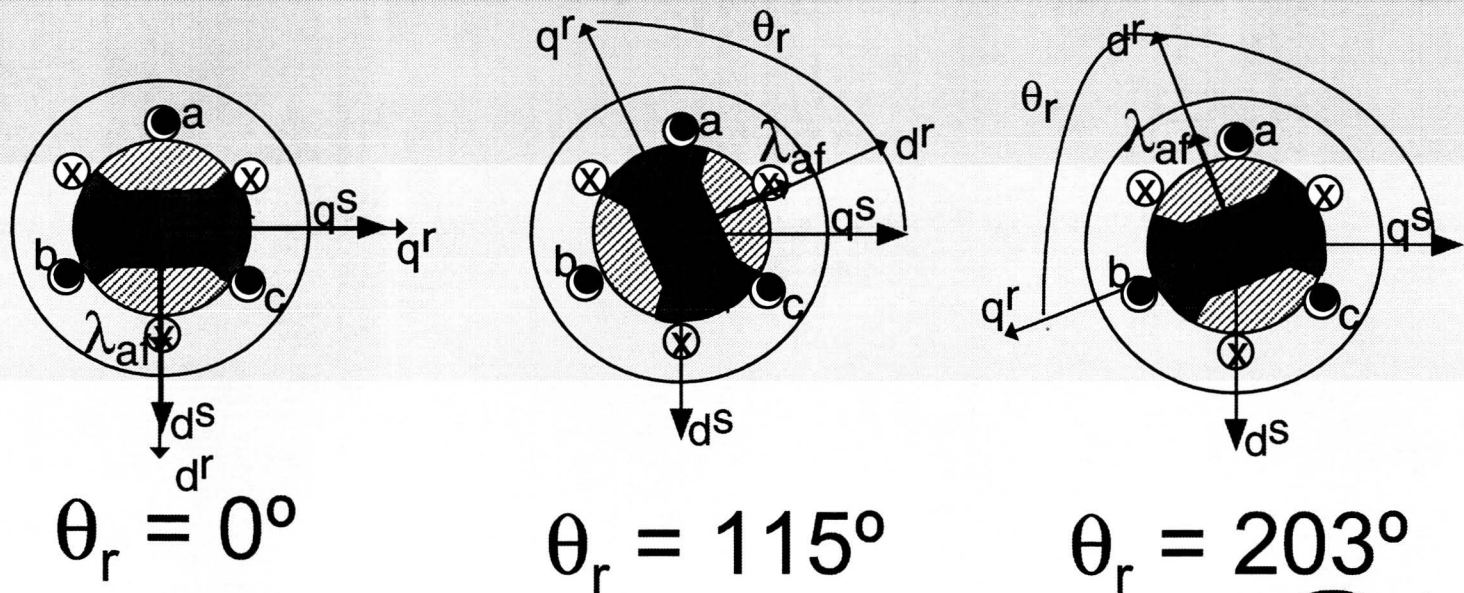
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Position Information Feedback Techniques

- Encoder or resolver
 - Mechanical device attached to shaft of machine
 - Speeds are too high for most of these devices
 - Adds length to shaft which reduces maximum speed



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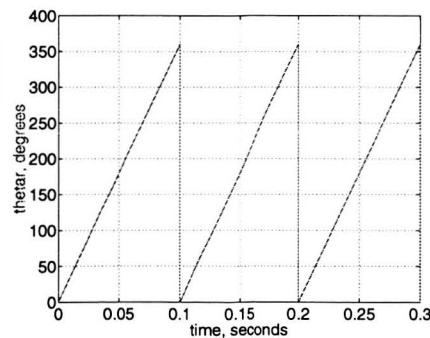
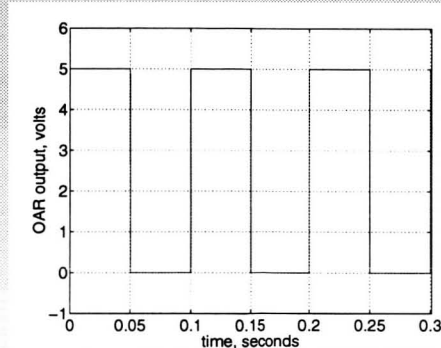
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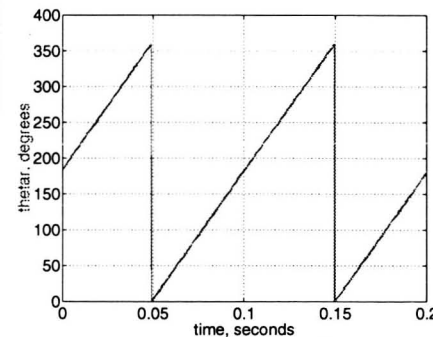
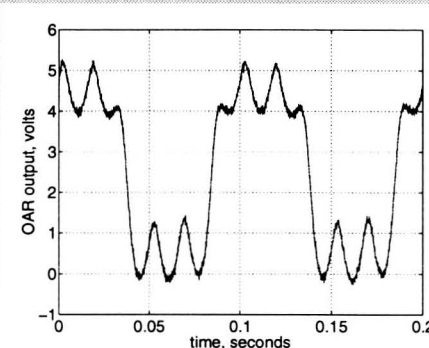
Position Information Feedback Techniques

- Once around signal
 - 1 rising edge per revolution based on optical signal
- Noisy signal, sample rate, start up, alignment

ideal



actual



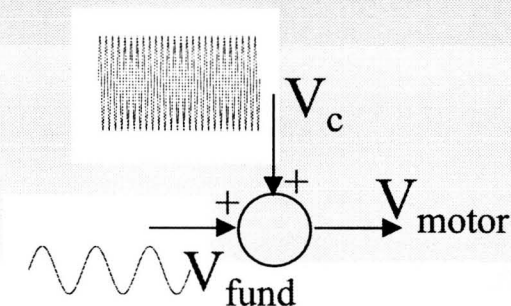
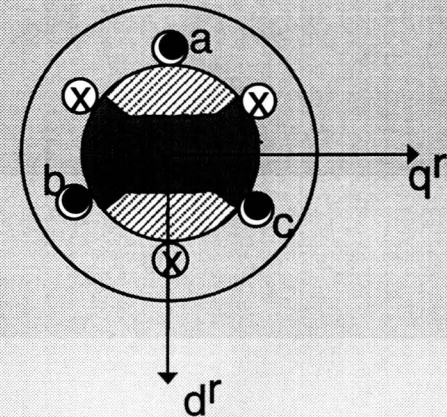
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Sensorless Position Estimation

- Low speed region
 - Requires “magnetic saliency”
 - $L_q^r > L_d^r$
 - Additional high frequency voltage carrier signal, V_c , added to fundamental
 - Resulting motor current will contain 3 components:
 - Fundamental: f_{fund}
 - “positive sequence”: $+f_c$ (~ 3 amps)
 - “negative sequence”: $-f_c$ ($\sim .25$ amps)
 - Position information contained in negative sequence component



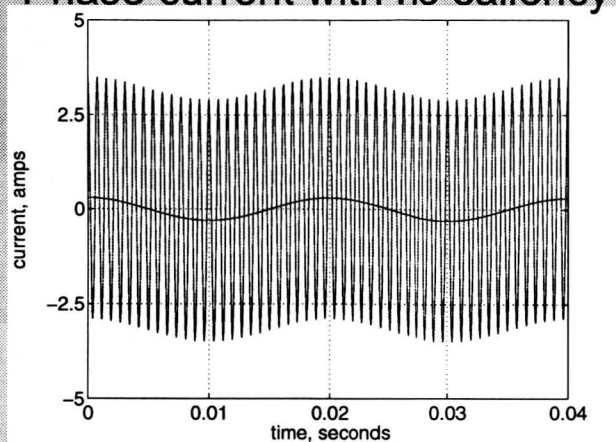
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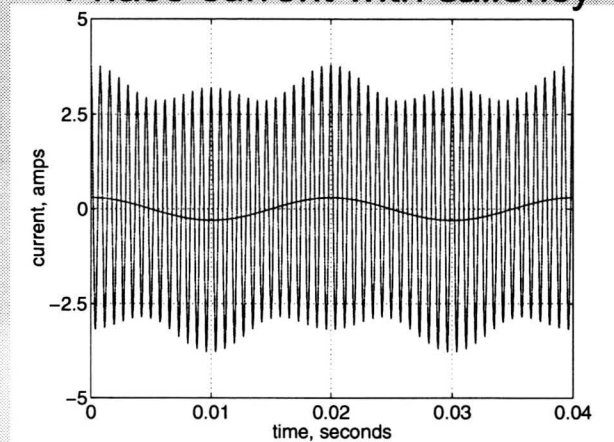


Self-Sensing Examples

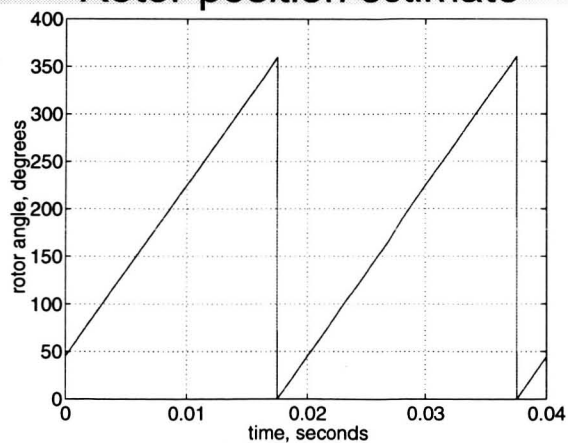
Phase current with no saliency



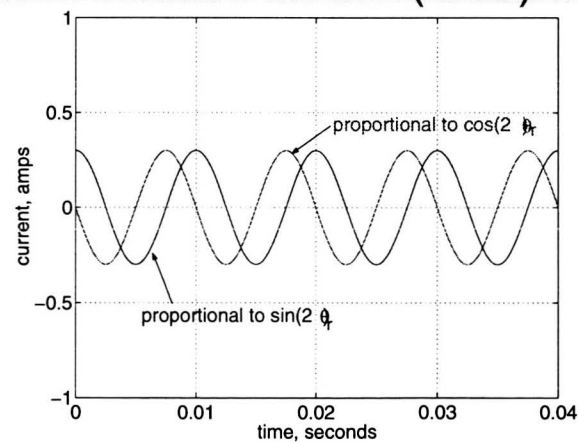
Phase current with saliency



Rotor position estimate



Filtered current (ideal)



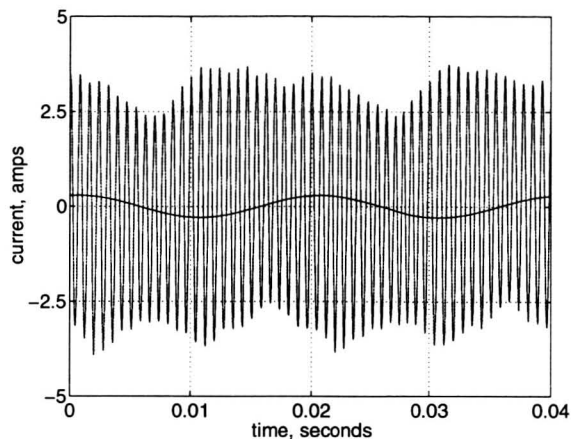
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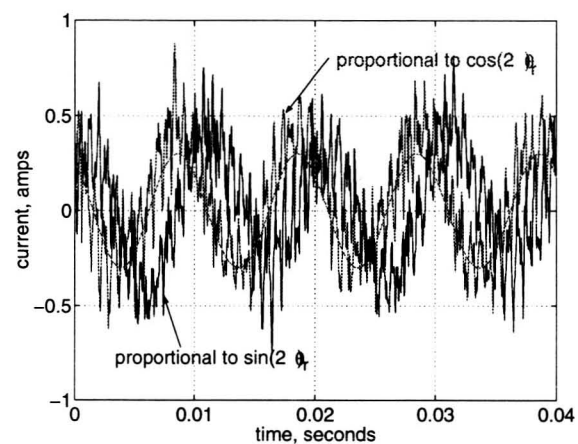


Self-Sensing: Experimental Results

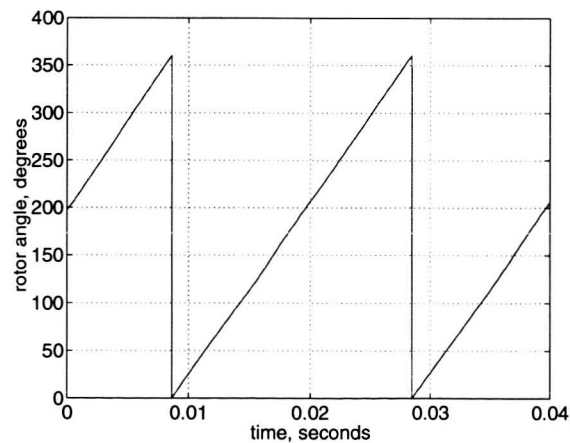
Measured phase current



Filtered current



Rotor position estimate



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“High” Speed Sensorless Control

- Back EMF Technique

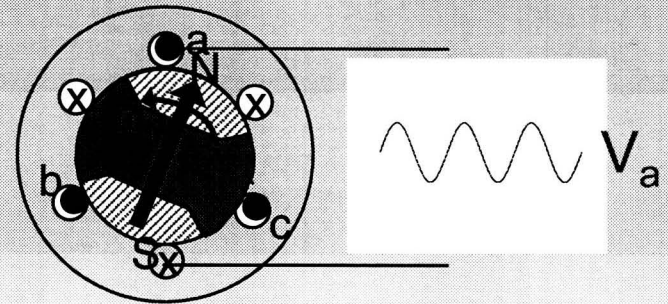
- Faraday’s Law: $V = d(\phi)/dt$

- $V_{\text{motor}} \propto d(\lambda_{\text{af}})/dt$

- $\lambda_{\text{af}} \propto \int V_{\text{motor}} dt$

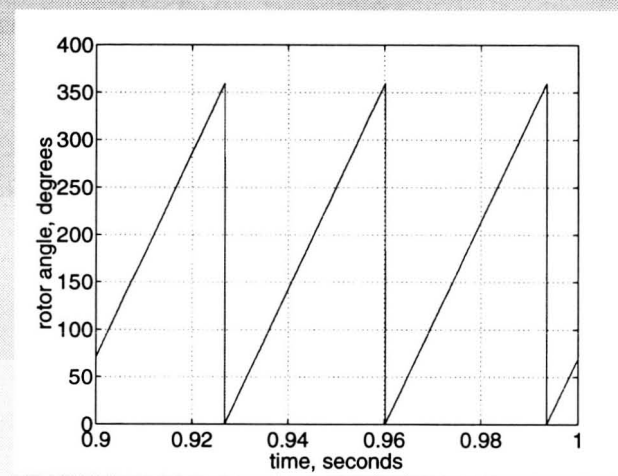
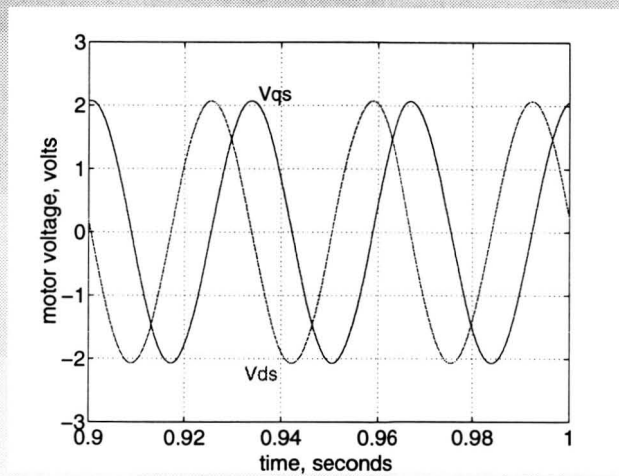
- Find θ_r from components of voltage vector

- $\theta_r \propto \tan^{-1} \left(\frac{\int (V_{\text{ds}} - i_{\text{ds}} R_s) dt}{\int (V_{\text{qs}} - i_{\text{qs}} R_s) dt} \right)$



- Actual motor voltage assumed to be equal to commanded motor voltage; current is measured.

Back EMF Example



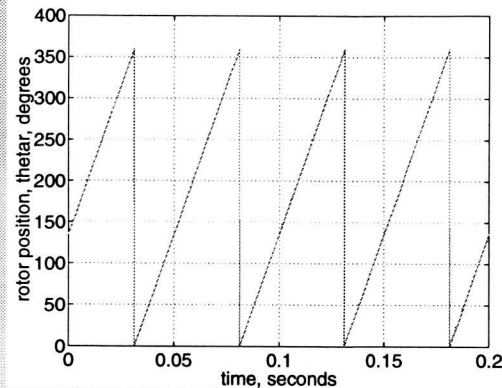
- Commanded motor voltages
- Estimated rotor position

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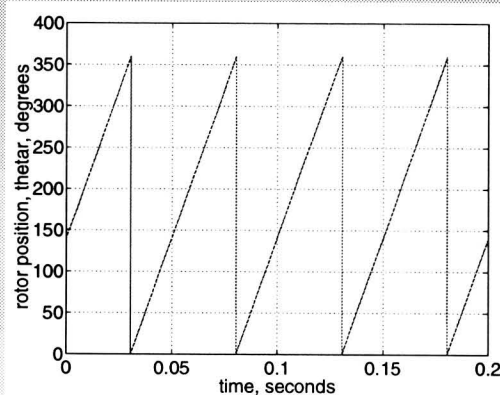
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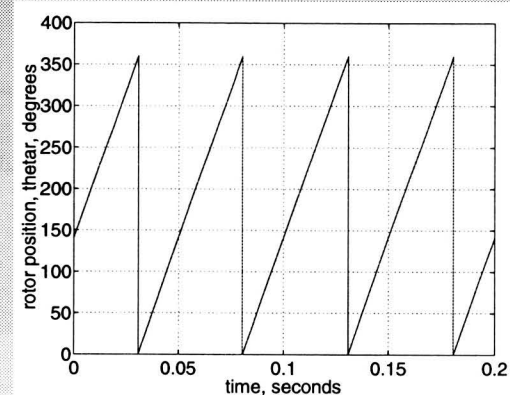
Rotor Position Estimation Accuracy



•OAR Estimate

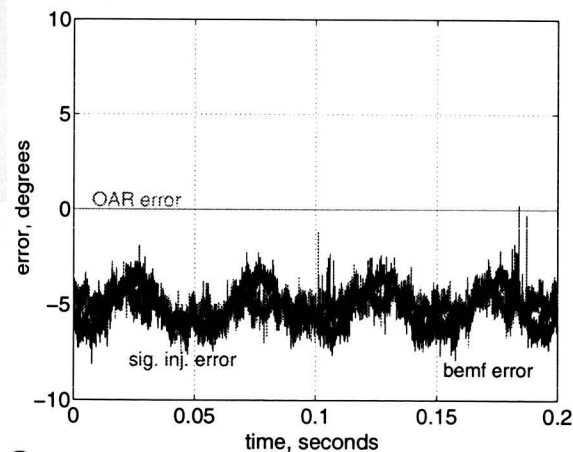


•Signal Inj. Estimate



•Bemf Estimate

•Relative Errors



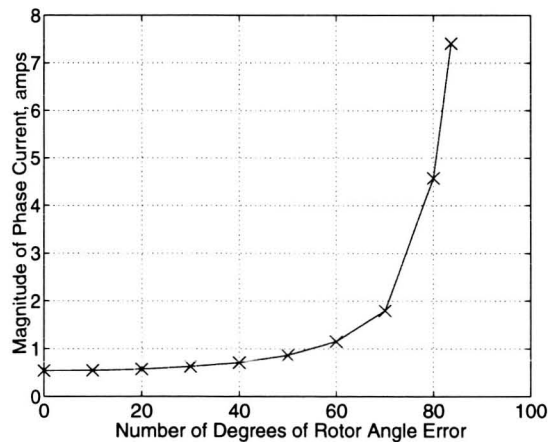
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Rotor Position Sensitivity

- Perfect θ_r estimate $\rightarrow i_d^r = 0$
- θ_r error $\rightarrow i_d^r \neq 0$ and $|i_s| \uparrow$



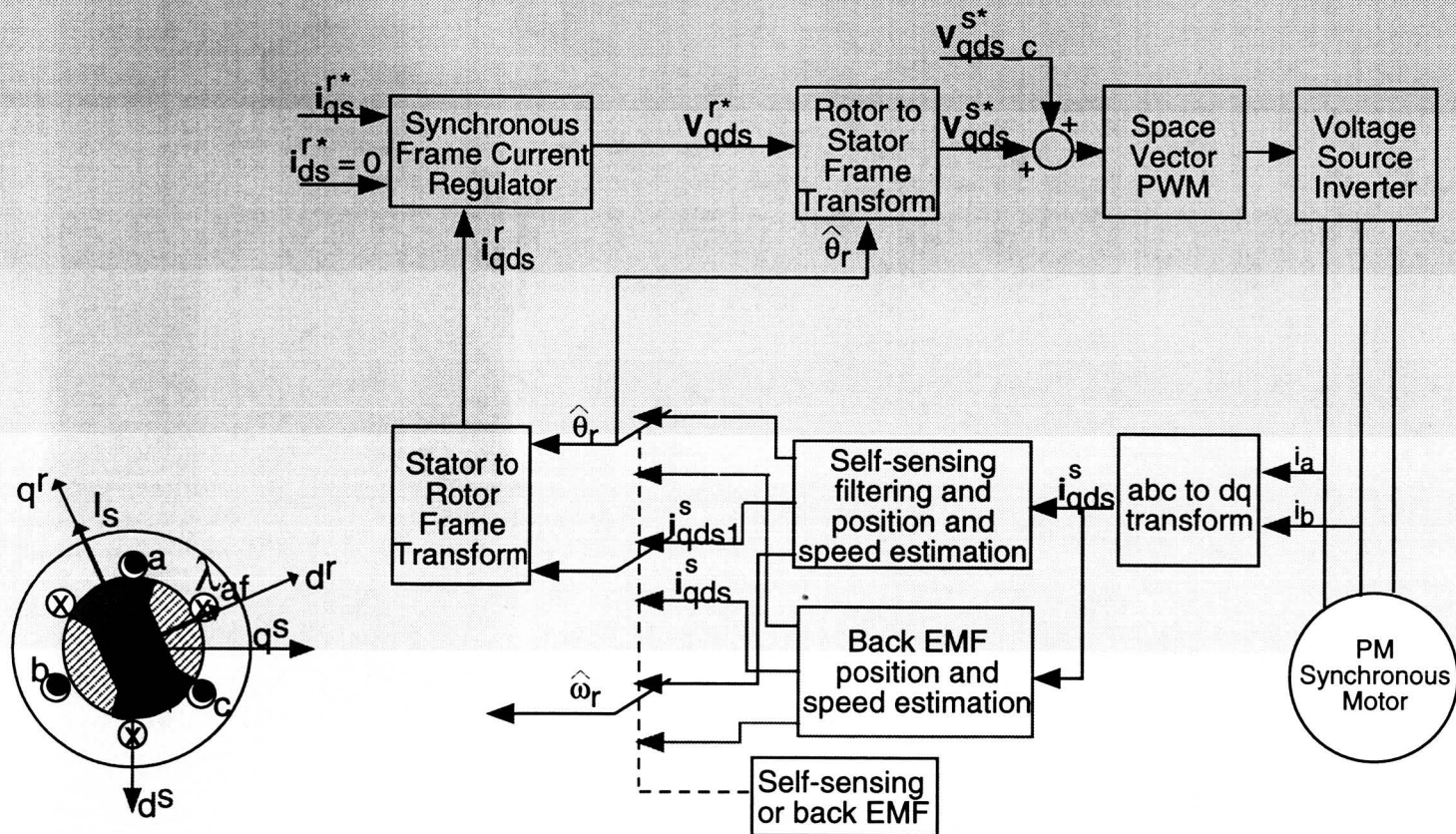
Phase current magnitude

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Block diagram of motor controller



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Flywheel Control

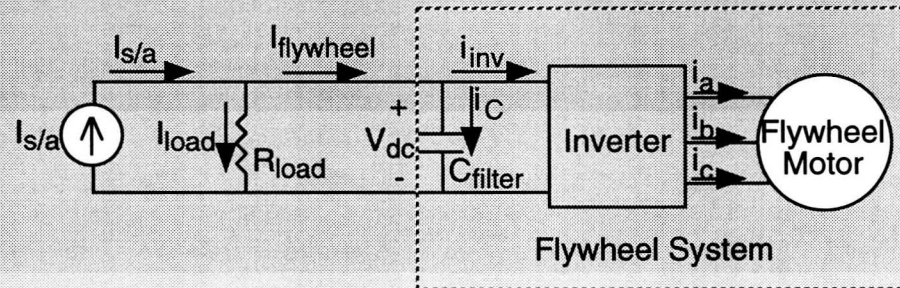
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Flywheel Modes of Operation

- Charge
- Charge Reduction
- Discharge



<u>Mode</u>	<u>Current</u>	<u>DC Bus Voltage</u>
Full Sun "Charge"	$I_{s/a} = I_{load} + I_{charge}^*$ $I_{flywheel} = I_{charge}^*$	Regulated by solar array system
Partial Sun "Charge Reduction"	$I_{load} + I_{charge}^* > I_{s/a} > 0$ $I_{charge}^* > I_{flywheel}$	Regulated by flywheel system
Eclipse "Discharge"	$I_{load} = - I_{flywheel}$ $I_{flywheel} < 0$	Regulated by flywheel system

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Inverter Current Control

- Charge Mode

$$\overline{I_{inv}} = I_{flywheel} = I_{charge}^*$$

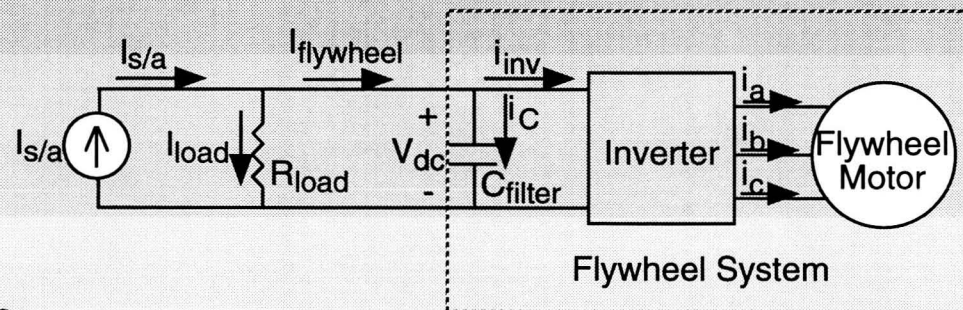
- Discharge Mode

$\overline{I_{inv}} \uparrow$ causes $V_{dc} \downarrow$

$\overline{I_{inv}} \downarrow$ causes $V_{dc} \uparrow$

- $\overline{I_{inv}}$ result of motor operation

How to control motor to achieve desired $\overline{I_{inv}}$?



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Motor Control Current

- Field Orientation Control

Rotor reference frame

Control currents DC at steady state

Motor torque proportional to current

$$\tau_e = \frac{3}{2} \frac{P}{2} \lambda_{af} i_{qs}^r$$

- Power Balance

Mechanical power $\approx$ electrical power

$$\omega_r \tau_e \approx P_{elec}$$

Average motor electrical power $\approx$ DC power

$$\frac{3}{2} \frac{P}{2} \lambda_{af} i_{qs}^r \omega_r \approx \overline{I_{inv}} V_{dc}$$

$$i_{qs}^{r*} = \overline{I_{inv}} * \frac{2V_{dc}}{3\omega_r \lambda_{af}}$$

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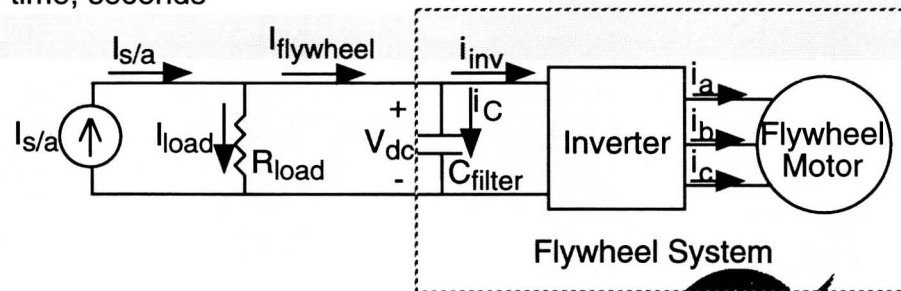
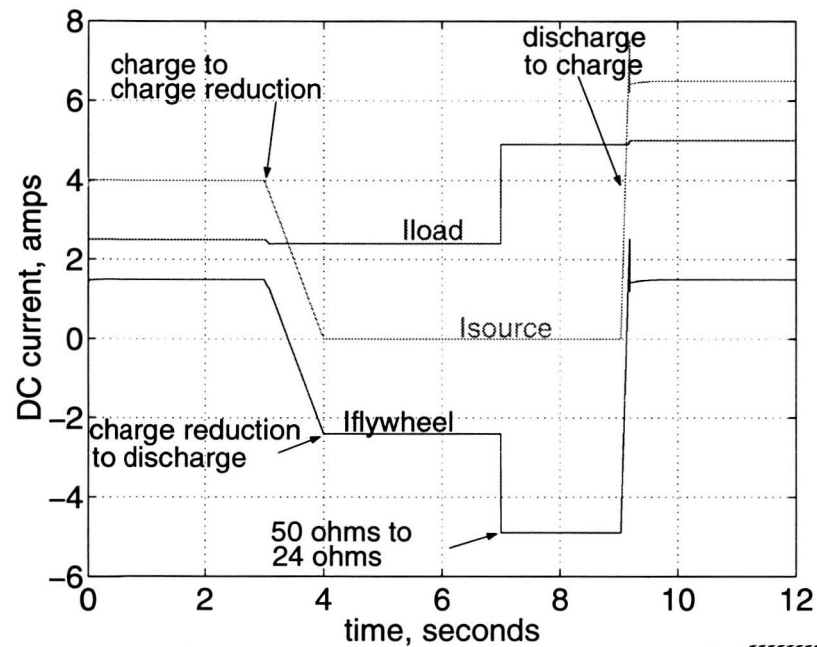


Control Procedure

- 1. Calculate $\overline{I_{inv}}^*$
Charge mode: regulate charging current
Discharge mode: regulate the DC bus voltage
- 2. Calculate the necessary motor current to achieve $\overline{I_{inv}}^*$
- 3. Regulate the motor and motor current through field orientation and a high bandwidth current regulator.



Simulation Results

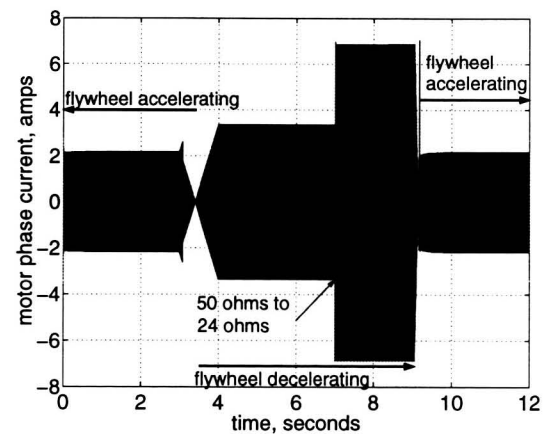
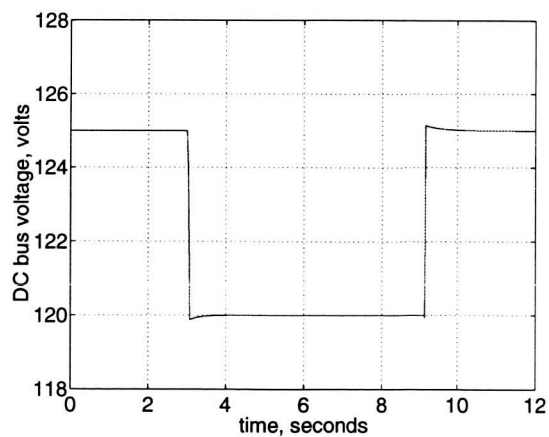
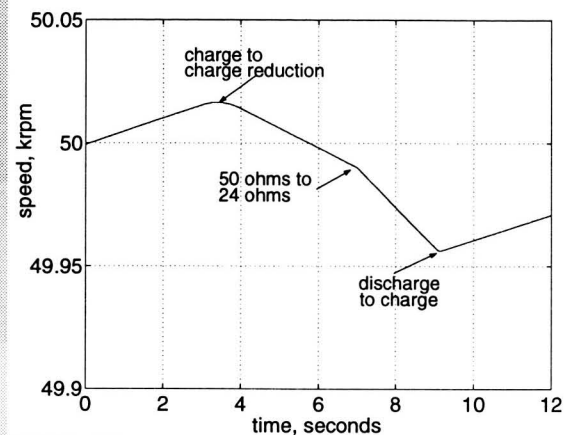
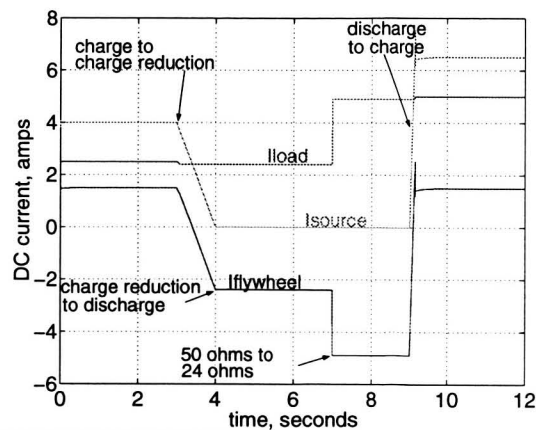


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Simulation Results (II)

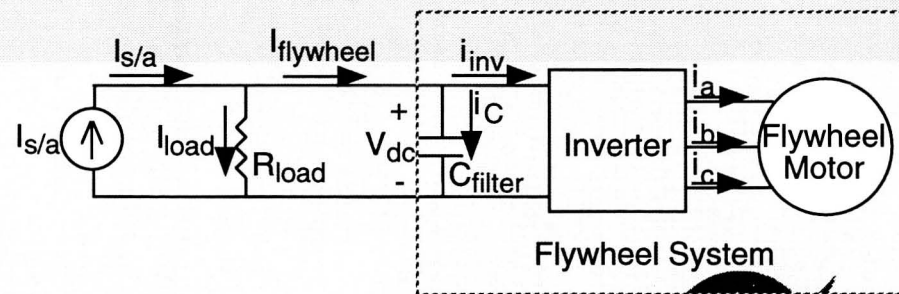
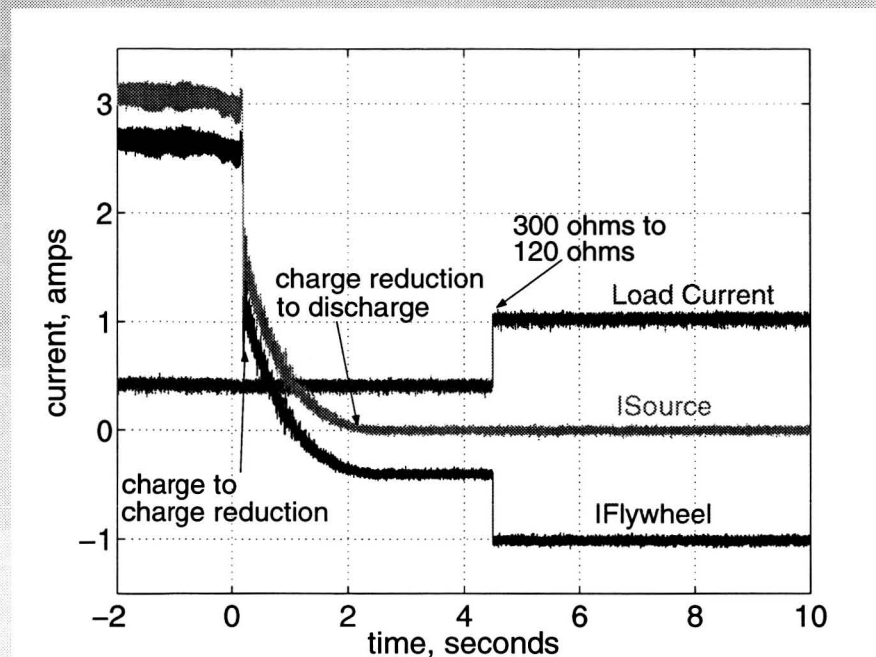


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Experimental Results (Charge to Discharge)

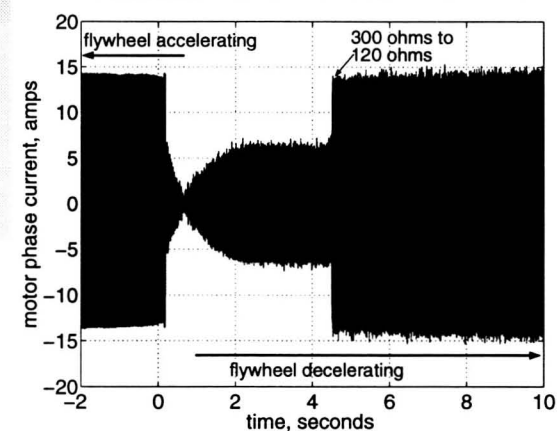
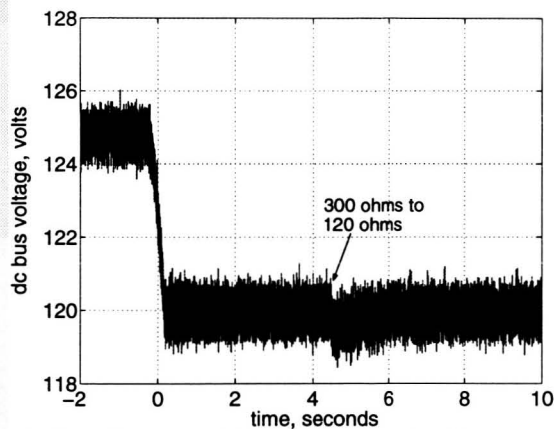
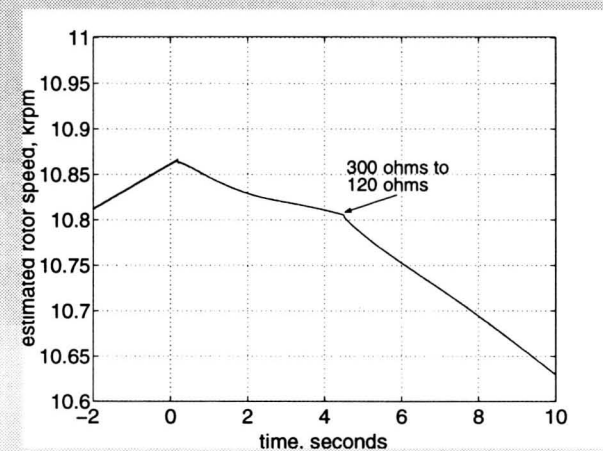
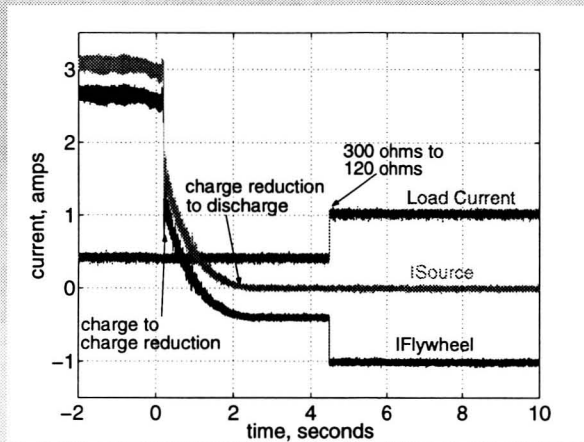


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Experimental Results (Charge to Discharge)

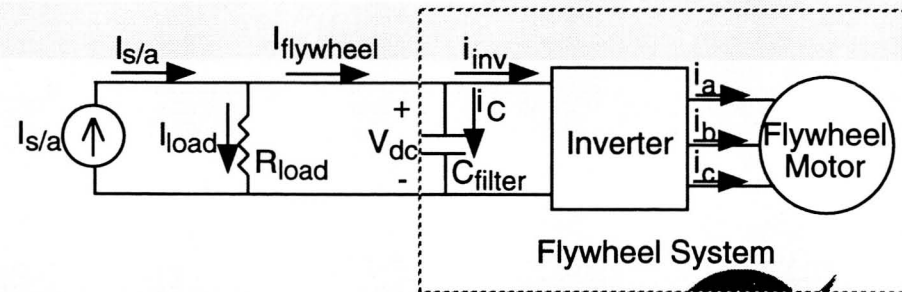
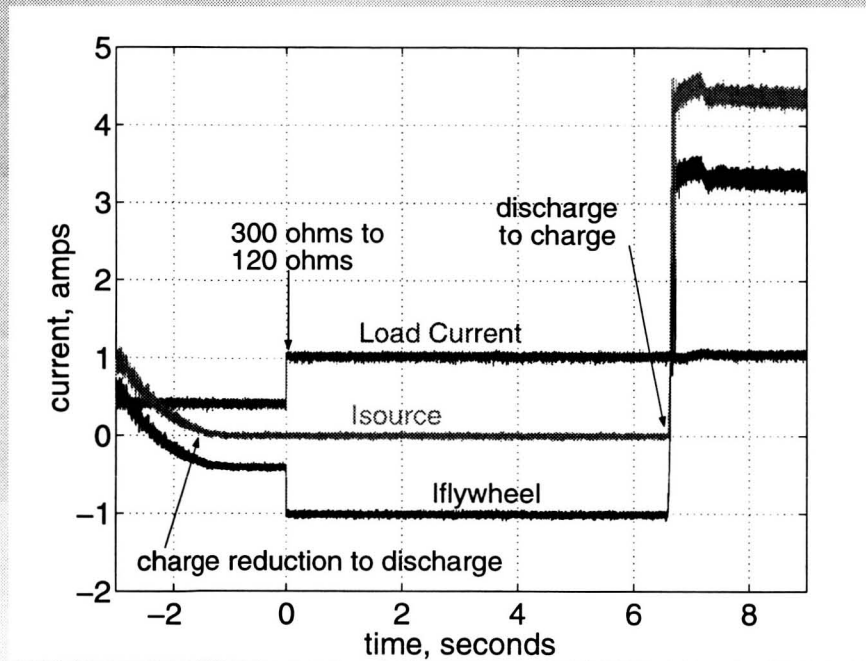


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Experimental Results (Discharge to Charge)

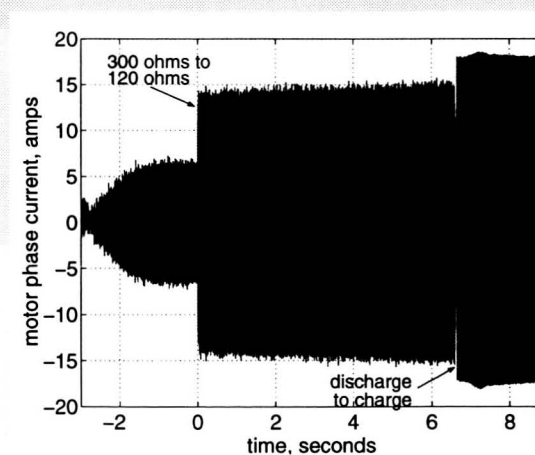
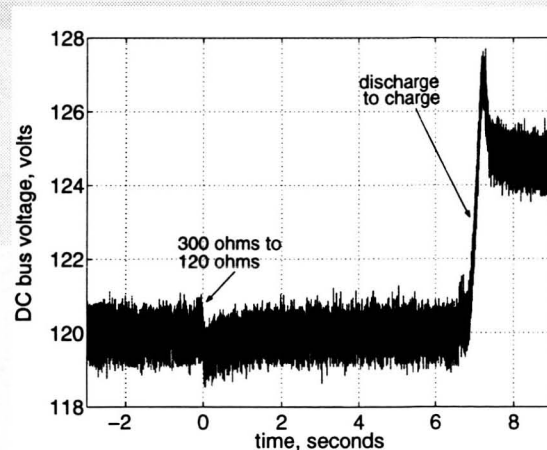
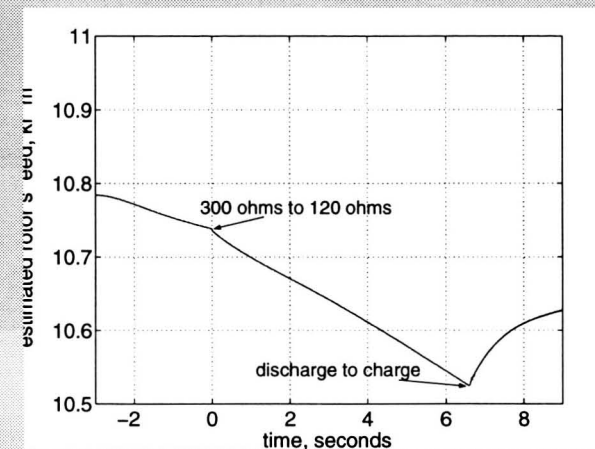
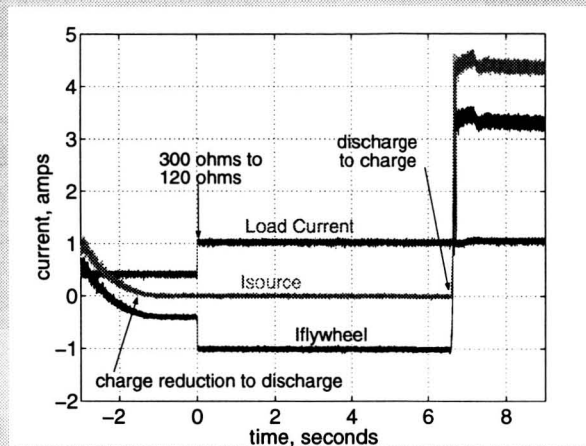


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Experimental Results (Discharge to Charge)



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Summary and Future Work

- Flywheel energy storage system control demonstrated
 - Sensorless control of permanent magnet machine
 - Low speed signal injection method
 - High speed back EMF method
 - 3 modes of operation: charge, charge reduction and discharge
 - Flywheel system regulates DC bus during discharge
- Multiple flywheel control is next
 - Spacecraft bus regulation, energy storage and attitude control
 - Initial feasibility shown within the last week!

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